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THE PERFORMANCE OF POINT LEVEL SENSORS IN LIQUID HYDROGEN

by

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ABSTRACT

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Seventeen manufacturers' point sensors have been tested for repeatability and time response from one atmosphere to 13.6 atmospheres. An analysis of the results by type and operating principle is presented. A description of the test apparatus and operating procedure is included. Possible application of point level sensors to space systems is summarized.

Author

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1. INTRODUCTION

The point level sensor test program described here was initiated in 1961 by the National Bureau of Standards as part of a state-of-the-art evaluation of cryogenic instrumentation for the National Aeronautics and Space Administration, Lewis Research Center. This is a summary of the work reported in quarterly reports to the sponsor and a detailed final report currently in press.

The selection of commercially-available liquid sensors was based on a survey of the literature, catalogue files, and information supplied by users of this type of equipment. Every attempt was made to include all units which appeared promising for the measurement of liquid hydrogen level.

Test objectives were established to provide a comparison based on reproducibility and response time in liquid hydrogen at various ullage pressures. The test method chosen to meet these objectives consisted of moving the sensors in and out of a quiescent liquid.

2. APPARATUS DESCRIPTION

The apparatus consisted of three major parts: (1) the dewar, (2) the actuating mechanism, and (3) the instrumentation and control system.

The dewar (figure 1) consisted of an inner stainless steel pressure vessel, a powder-vacuum annulus space, and a carbon steel outer shell. Within the dewar was a welded cylindrical stillwell open at the top. Liquid hydrogen was transferred in through the dewar bottom. During filling, liquid rose along the outside of the stillwell and then spilled inside. By using this configuration, boiloff and undesirable surface perturbation were held to a minimum.

*Guest worker at Cryogenic Engineering Laboratory Division, National Bureau of Standards, from Arthur D. Little, Inc., Santa Monica, California.

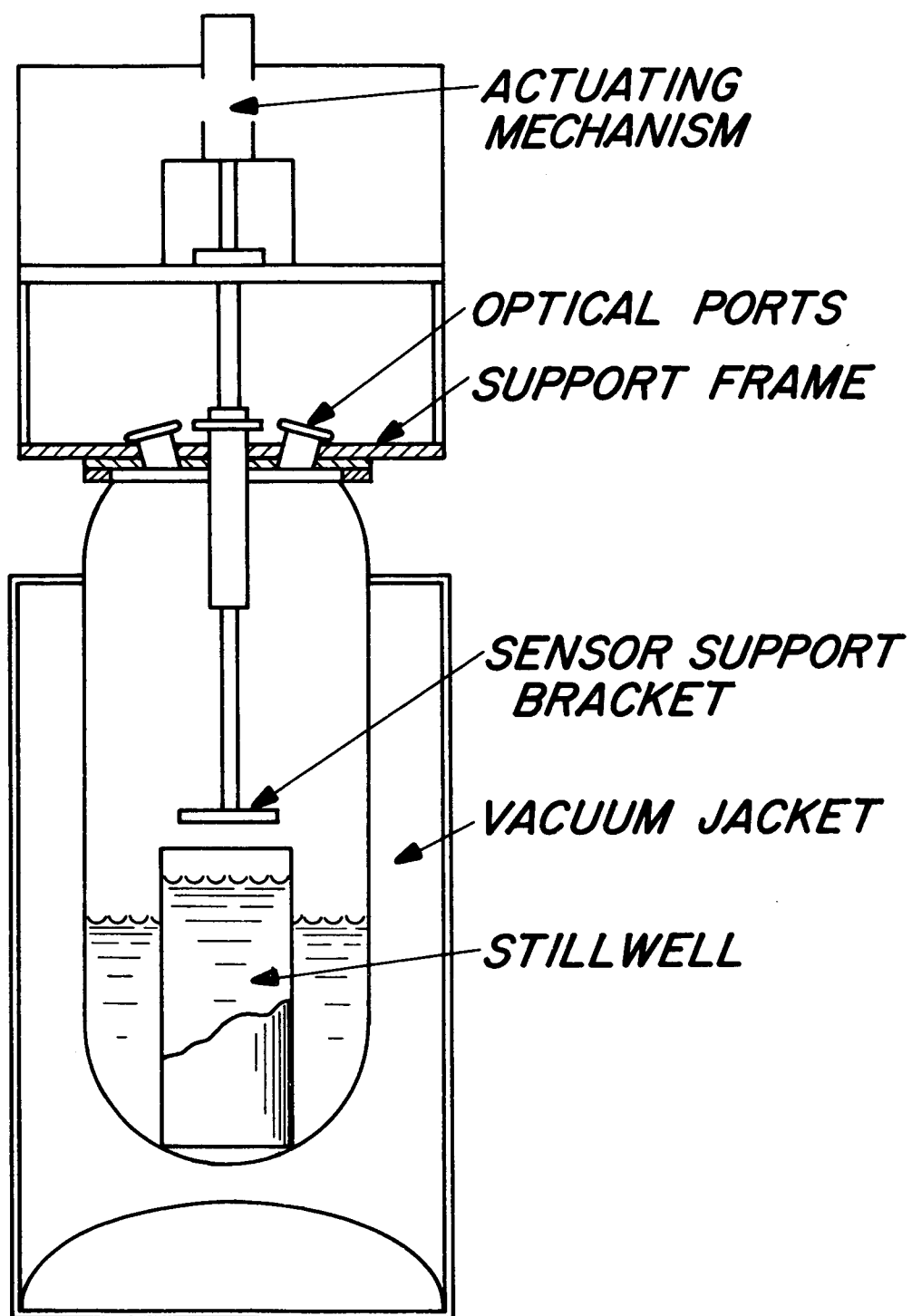


FIGURE 1 :

TEST DEWAR ASSEMBLY

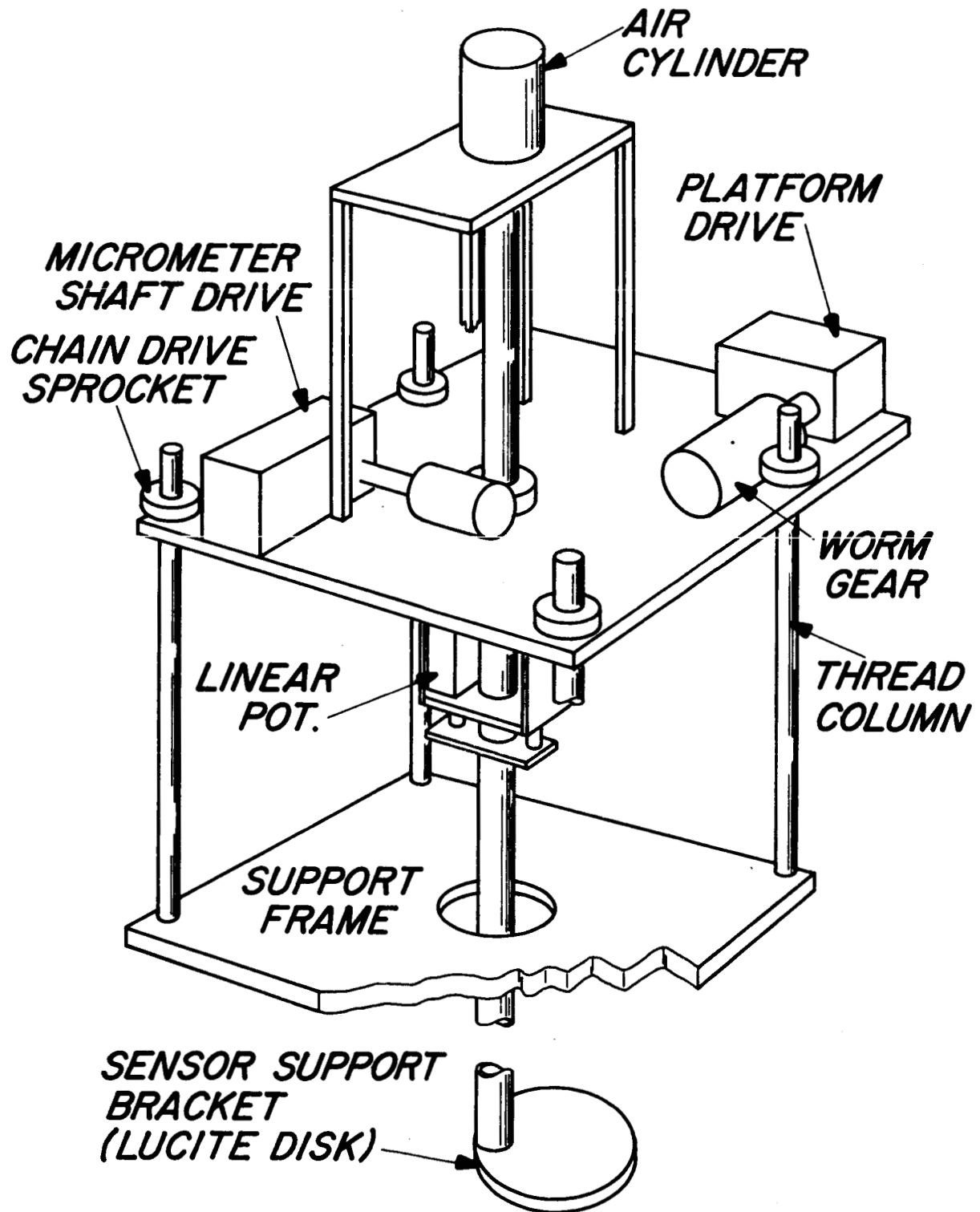


FIGURE 2: ACTUATING MECHANISM

The dewar cover plate was penetrated by a shaft and seal, "ball bushing" housing, two optical ports, instrumentation leads and a pressure tap.

The actuating mechanism (figure 2) provided three methods of moving the sensors relative to the liquid hydrogen surface. A worm-gear shaft drive was used for shaft excursions up to one inch. For initial positioning of the point sensors relative to the liquid surface, a worm-gear chain drive was used to move the upper platform assembly. This platform drive was also used occasionally for sensor testing when the band of data points exceeded the measurable shaft travel span. For rapid cycling of sensors in and out of the liquid an air cylinder drive was used.

The instrumentation and control system was built for remote monitoring and control capability.

Sensor outputs were visually observed as well as recorded. A 1-inch linear potentiometer was used to measure shaft position and a 6-inch linear potentiometer was used to follow shaft excursions during rapid cycling. When platform instead of shaft drive was used, platform position was determined by multiplying the measured travel time by a known displacement rate.

Several timed calibration runs of platform excursions in both directions proved the displacement error to be less than 0.001 inch absolute.

End-to-end calibration checks performed on the shaft position monitoring system demonstrated that the absolute accuracy was within the resolution of the linear potentiometer (0.0021 inch). Precision gauge blocks inserted between the linear potentiometer and its actuating bracket were used as the measurement reference. Drive speeds were as follows:

| | |
|--------------------|--|
| Shaft Drive | 0.001 in/sec. |
| Platform Drive | 0.010 in/sec. |
| Air Cylinder Drive | Adjustable (Range used: 23-60 in/sec.) |

3. TEST CONFIGURATION

The development of a standard sensor with a proven absolute accuracy was not within the scope of the program. Other methods of locating the liquid-vapor interface relative to any sensor were considered, but proved too inaccurate for purposes of this evaluation.

Preliminary tests indicated that a sensor could be checked against itself by running the unit in and out of liquid several times. The initial approach was to determine how repeatably each sensor would indicate "wet" on liquid immersion and "dry" on emergence. The validity of this approach was proven in the data analysis from the first sensor tests and continued to manifest itself throughout the entire test series.

To conserve liquid hydrogen and set-up time, several sensors were installed in the apparatus at the same time. The installation concept of one such group of sensors on a transparent plastic disk is shown in figure 3.

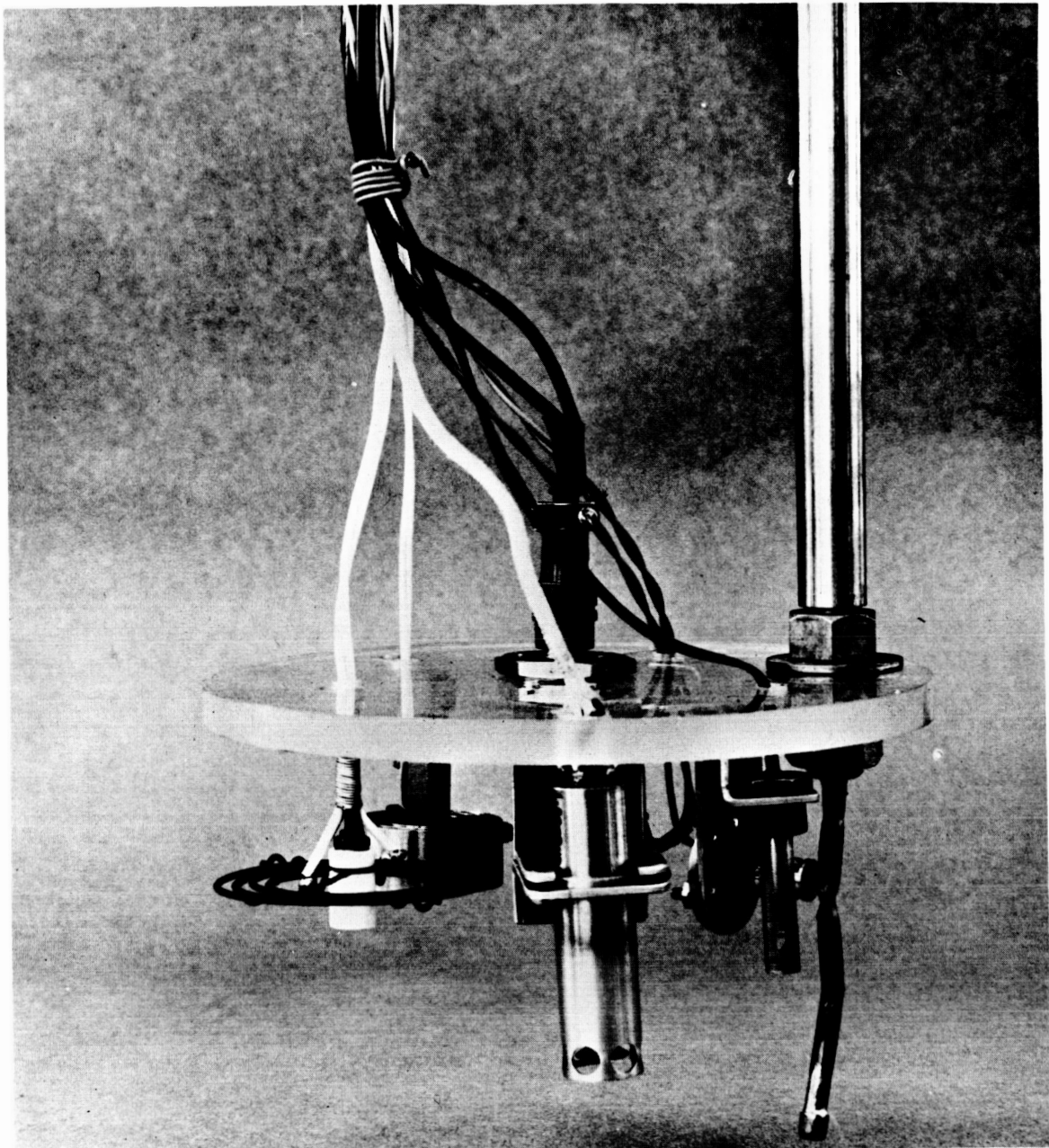
For each group installed in this manner, it was visually determined that surface perturbation caused by one sensor did not significantly affect the performance of the others. Sensors partially or completely submerged during testing of a particular sensor, displaced a constant volume, and since generally the dead band of sensors was narrow, level variations were not significant.

To test for sensor response time, a high shaft speed was desirable. Errors in response time resulting from liquid boiloff and measurement tolerances on actual sensors position, could be kept below 2 milliseconds by using shaft speeds between 23 in/sec and 60 in/sec. The available 6 inch stroke was sufficient to insure that all sensors were completely submerged at the bottom end of the stroke and completely out of liquid at the top.

4. TEST SPECIMENS

All the sensors tested were transducers which responded to the change in one of the physical property coefficients at the liquid vapor interface to provide a varying output signal coefficient.

Listed in table I are the sensors by type and by their predominant sensing coefficient.



0 2 4 6 8
SCALE IN INCHES

A Typical Group of Sensors Mounted to a Plastic
Disk for Testing

Figure 3

| CLASSIFICATION OF POINT SENSOR | |
|---------------------------------------|----------------------------------|
| <u>SENSOR TYPE</u> | <u>COEFFICIENT SENSED</u> |
| RESISTIVE | HEAT TRANSFER |
| CAPACITIVE | DIELECTRIC CONSTANT |
| OPTICAL | REFRACTIVE INDEX |
| PIEZOELECTRIC | ACOUSTIC IMPEDANCE |
| MAGNETOSTRICTIVE | ACOUSTIC IMPEDANCE |
| VIBRATORY | VISCOUS DAMPING |

TABLE 1

4. 1 Resistive Type

The large difference in the heat transfer rate which occurs between the sensor when in liquid and the sensor when in vapor produces a temperature and corresponding resistance change in the sensing element. As this resistance change reaches a threshold value it activates an output signal.

4. 2 Capacitive Type

The difference in dielectric constant between vapor and liquid produces change in sensor capacitance. This change is detected and amplified to provide a usable output signal.

4. 3 Optical Type

The change in refractive index between liquid and vapor around an optical prism provides a variation in internally reflected light intensity. The light intensity is sensed by a solar cell whose varying output is detected and amplified.

4. 4 Piezoelectric Type

The change in acoustic damping which occurs when the medium changes from liquid to vapor causes a change of energy dissipation in the resistive component of a crystal's equivalent impedance. The Q of the circuit decreases with the crystal in liquid, damping oscillations. Circuit oscillation is detected to provide an output signal.

4. 5 Magnetostrictive Type

This type sensor also uses the acoustic damping difference between liquid and vapor. A driving coil produces an oscillating magnetic field around a tubular magnetostrictive element. The element elongates and contracts at ultrasonic frequencies. A separate coil senses the element motion and provides a positive feedback signal to sustain circuit oscillation. When the element is restrained (e. g. , when in liquid hydrogen) the feedback signal is lost and oscillation stops. A detector circuit rectifies the oscillations to drive an output device.

4.6 Vibratory Type

The difference in viscous damping between liquid and vapor provides a variation in oscillation of a mechanical paddle which is driven by an oscillating solenoid slug. A similar slug mechanically linked to the paddle and oscillating in the magnetic field of a pickup coil produces a varying voltage that is converted to a usable output.

5. TEST PROCEDURES

Repeatability and response tests were performed at the following dewar pressures: 2, 20, 50, 100, 150, and 200 psig.

Twenty cycles in and out of the liquid were run for the repeatability tests at each of the six pressures. Five cycles in and out of liquid were run for the response tests at each of the six pressures. Ten seconds were allowed at each end of the shaft stroke to obtain correct sensor indication. It was determined that, during the five cycles, the liquid level decrease caused by splashing or boiloff was not significant.

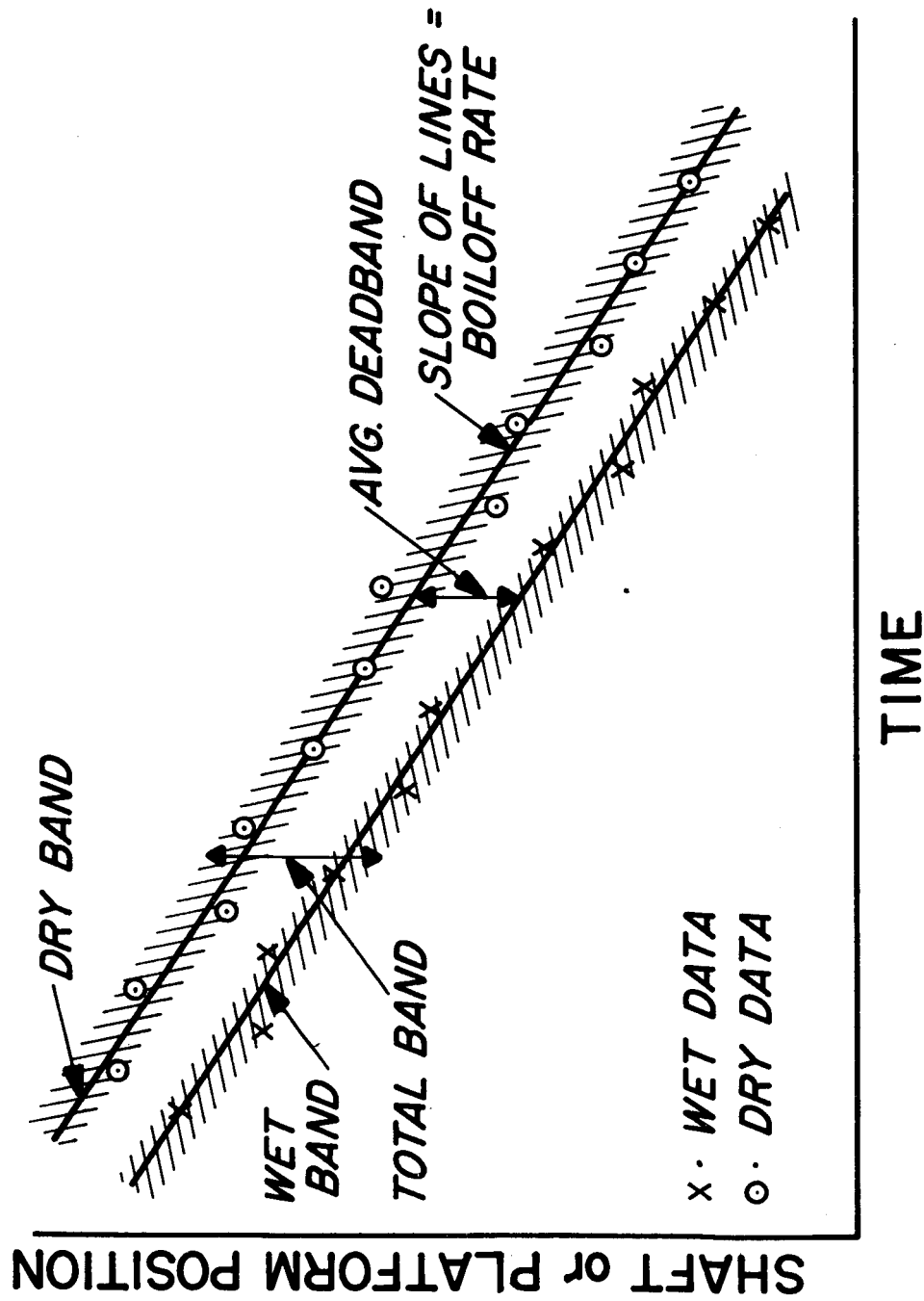
6. RESULTS

6.1 Data Reduction

Repeatability test data were reduced and plotted as shown for a hypothetical case in figure 4.

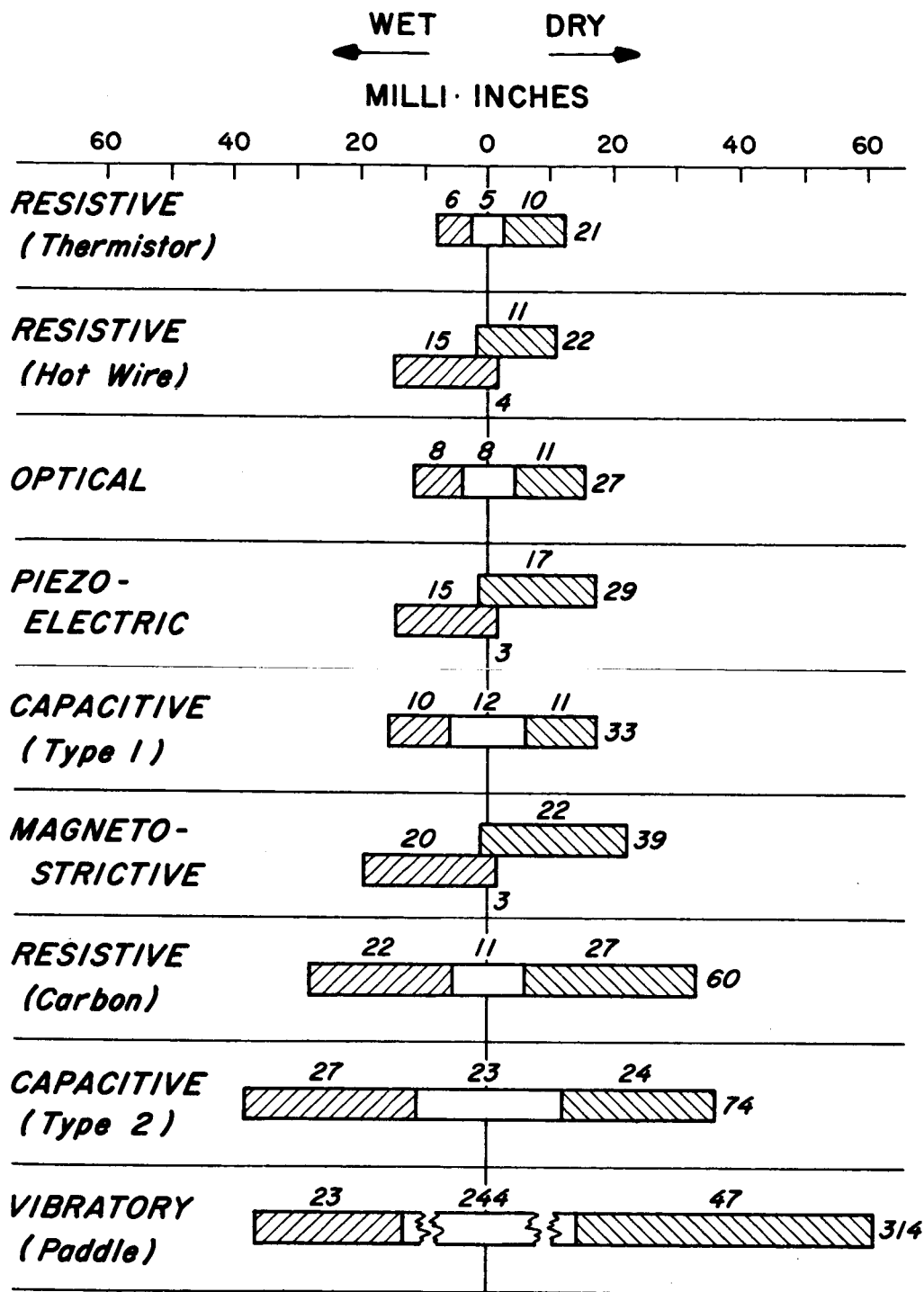
The slope of the lines shown depict the boiloff rate for a particular run.

All reasonable wet and dry points fall within the respective bands. The "total band" encompasses all readings, dry and wet. The "dead band" is the area where no readings fall. The dead band is caused by intentional tolerances associated with the sensor triggering point and such considerations as differences between output relay pull-in and drop-out currents, and by other experimental uncertainties. Overlap of dry and wet readings were also observed in some cases; these may be partially explained by meniscus and surface tension effects. Response times were taken directly from the recorder charts and tabulated.



HYPOTHETICAL REPEATABILITY DATA PLOT

FIGURE 4



REPEATABILITY INDICATION DATA FOR TESTS IN
LIQUID HYDROGEN BY LEVEL SENSOR TYPES.

(Average of 2, 20, and 50 psig tests)

FIGURE 5

6.2 Data Summary

Repeatability data are presented in figure 5 and response data have been averaged in figure 6. The results shown are a representative average of individual sensor data taken at 2, 20, and 50 psig.* In figure 5, a blank space between the cross hatched bars means that a dead band existed between wet and dry bands. If the cross hatched areas overlap, it means that the wet and dry bands overlapped one another.

To provide a more meaningful comparison between sensor types, two of the sensor categories mentioned earlier have been further subdivided. The resistive type comprises hot wire, carbon resistor, and thermistor sensors. The capacitive sensors have been separated into small, lightweight probes and control units designed primarily for use in aircraft and missiles (Type I), and the rugged, and larger devices intended for facility or ground system application (Type II). No attempt has been made in the presentation of data in figures 5 and 6 to rate or rank any of the sensors. Only by knowing the application can a suitable device be selected.

6.3 Qualitative Conclusions

In addition to the specific quantitative data presented above, some qualitative conclusions regarding specific sensors were drawn during the course of testing.

6.3.1 Hot Wire Sensors

On occasion, when these units were positioned to within less than one-half inch above the liquid surface, they indicated wet briefly during a pressure blowdown test. In general, however, this type of sensor gave reliable indications.

* Above 100 psig, with some exceptions, the repeatability and response performance characteristics of the liquid sensors deteriorated. Since many explanatory notes are required to present these data, they have not been included in this paper.

6.3.2 Thermistor and Carbon Resistor Sensors

These sensors performed satisfactorily, in that no false indication was noted even during the dewar filling operation and during pressurization or depressurization. Recorded response times on emergence were relatively fast. Some manufacturers have installed a separate heater wire winding around the sensing element to speed up the temperature rise and thereby improve the recovery time.

6.3.3 Capacitive Sensors

Type I capacitance probes experience only a small rise in capacitance on immersion. These probes therefore require refined control units. Attractive features are: (1) pseudo guard circuits and the three-wire approach which makes these units independent of cable length, and (2) only a detector bridge unbalance from an increase in probe capacitance can result in a wet indication.

Most of the Type II circuits required no particular refinement due to the relatively large capacitance change available. However, instances of false indications due to a decrease in capacitance with temperature were noted during preliminary acceptance testing. The majority of the Type II units are sensitive to cable length.

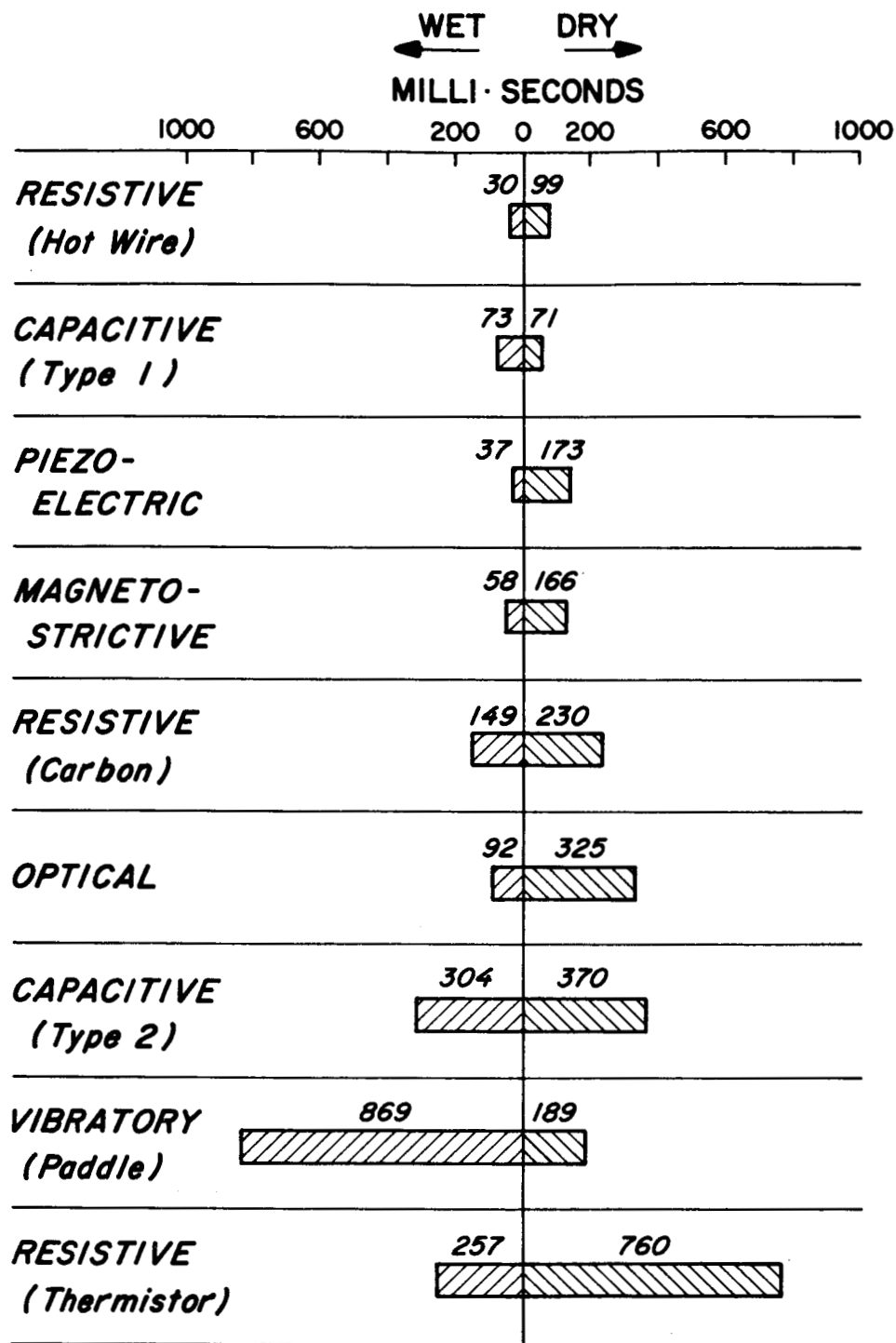
Cross-talk problems with capacitance type sensors were encountered only when probes were spaced less than 1/4-inch apart.

6.3.4 Optical Sensors

Optical sensors exhibited satisfactory performance throughout the test program. A black or other non-reflective surface should be used opposite the sensor tip. Extraneous light introduced to the solar cell may cause the sensor to retain a dry indication when wet.

6.3.5 Magnetostrictive Sensors

Some pressure sensitivity was noted during early tests. Increasing the gain and thereby reducing the sensitivity somewhat, eliminated this problem.



TIME RESPONSE INDICATION DATA IN LIQUID
HYDROGEN BY LEVEL SENSOR TYPES
(Average of 2, 20, and 50 psig tests)

FIGURE 6

It was found that a horizontal installation, with the sensor axis parallel to the liquid surface, was mandatory for repeatable operation. One manufacturer preferred a 15° inclination to the horizontal, which appeared to be most suitable for his particular probe tip design. A variety of probe configurations were tested. The majority of the units utilized a diaphragm as the sensing element.

To improve on relatively slow cooldown times, some manufacturers of magnetostrictive sensors have installed a low mass pseudo diaphragm, which cools down quickly and provides the required damping to the primary diaphragm. One manufacturer supplied a special circuit which detected minor variations in the oscillation envelope caused by the boiling liquid. This circuit, although tested only in nitrogen, responded immediately and produced the proper sensor indication until boiling subsided, whereupon normal circuit operation resumed.

6.3.6 Piezoelectric Sensors

A great number of spurious indications were noted in the process of preparation for test, during test, and while testing other sensors. Pressure sensitivity was a continuous problem and frequent adjustments of the control unit were required. The sensor probes were fragile. The piezoelectric sensors require further development before they can be recommended for aero-space liquid hydrogen systems.

6.3.7 Vibrating Paddle

Operation was satisfactory throughout the test program. The unit was relatively large and heavy, although this did not appear to affect cooldown time. The probe must be firmly anchored for any tests, as the performance of this device deteriorates when attached to a resilient mount.

7. APPLICATION OF POINT SENSORS TO MILITARY AND SPACE VEHICLES

7.1 Propellant Loading

Point sensors have been used during propellant transfer to signal presence or absence of liquid in the facility transfer line, to switch from rapid fill to fine fill when the missile tanks reach a pre-determined (e. g. , 95 percent full) level, to cut off fine load at the 100 percent full level, and to control topping flow in order to maintain the 100 percent level. The latter has been successfully accomplished on Titan I by using a single point sensor. Point sensors have been used to provide overfill warnings. In space systems, where the missions may vary, several groups of 95 to 100 percent sensors may be installed.

7.2 Engine Cutoff

To prevent erratic operation or even catastrophic stage failure, the engines must be shut down prior to complete propellant depletion. Point level sensors have, therefore, been installed in the pump suction lines to signal the absence of liquid and thereby initiate engine cutoff.

7.3 Propellant Utilization

The use of point sensors for propellant utilization may be accomplished provided the conditions of the fluid are known. The use of point sensors with a sub-cooled liquid has been accomplished. Liquid hydrogen level changes caused by decreasing ullage pressures and resultant bulk density decrease must be known and evaluated, before system performance can accurately be predicted.

Propellant utilization systems have been used to attain minimum propellant residual at engine cutoff by controlling outflow of one of the propellants within the limits of mixture ratio tolerances. Signals from point level sensors, which are spaced at various "percent full" levels in both the fuel and oxidizer tanks, can be compared on a time basis and processed through a computer. The computer may then provide the necessary mixture ratio control commands to a flow control valve. Such a system is presently used on the Atlas Standard Space Launch Vehicle (SSLV) and has been proposed for upper stages of Saturn.

7.4 Propellant Monitoring

Point sensors may also be used to monitor the depletion of propellants during flight. For this purpose, sensors may be positioned in a manner similar to that used for PU systems. Sensor signals are telemetered back to the ground stations or used for zero reference and calibration.

8. OTHER USES

Point sensors may, of course, be made to other cryogenic fluids.

9. SUMMARY

While not duplicating any specific application, the tests performed on seventeen manufacturers point level sensors have provided a common basis of comparison of their performance in liquid hydrogen.

It has been found that a number of commercially available sensors do perform satisfactorily in liquid hydrogen and that some selection for this and other applications is possible.